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A METHOD FOR ZERO CARBON DESIGN USING MULTI-OBJECTIVE OPTIMISATION

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ABSTRACT

The aim of this paper was to investigate optimum methods for zero carbon retrofit, that would not only result in achieving zero carbon status of a building, but would also maintain this status in future climate, using environmental, social and economic criteria. The environmental criteria included energy and carbon emissions. Thermal comfort was considered under the social criteria. The financial criteria included the retrofit cost.

A basic box model was used to run simulation tests, in order to investigate conflicting constraints of environmental, social and economic criteria, all under current and future climate. However, to search for the optimum retrofit solution, a multi-objective optimisation, was deployed as a decision aid technique. DesignBuilder software was utilised to create the base model, and JEPlus with EnergyPlus was used as an engine to run the multi-objective optimisation, with three objectives; carbon emissions, cost and comfort.

Trade-off relationships between carbon and comfort and carbon and cost have been plotted as result of optimisation, and design solutions to help maintain the zero carbon performance in the future weather have been identified in order to decrease the chances of overheating and excessive energy use for cooling.

INTRODUCTION

The UK set a target to reduce its carbon emissions by 80% by 2050, the relative to 2000 emissions, according to the UK's independent climate change committee recommendation (NHBC, 2009). It is estimated that 80% of the houses in 2050 will be houses that exist now, highlighting the importance of retrofit (Boardman et al., 2005).

The building sector is the largest user of energy in the European Union (EU). Therefore, there is a need to enhance the new and existing building stock. Passive strategies, energy efficiency measures and innovative technologies for buildings are well known within the field. However, the decision making process to identify the best combination that would result in the best possible scenario is a complex process. There are several aspects that need to be coordinated: energy and environmental, financial, social, legal and others (Asadi et al., 2012).

These early stage design decisions, whether for new build or retrofit, will highly influence the building performance over the 50-100 years of its lifetime.

Future predictions of temperatures show an increase in Cooling Degree Days (CCD), which would result in more air-conditioning, in order to maintain thermal comfort levels, consequently increasing the demand for fossil fuels (UKCIP, 2010).

Adaptation measures are therefore essential for both new built and existing buildings along with mitigation measures in the context of climate change.

With more criteria to cover, the complexity of the design decision process will increase, so will the need for better decision support tools. Energy modelling has been used extensively to predict the overall building performance. However, the number of annual results increases exponentially with the number of simulated parameters, potentially leading to a large solution space where searching for the optimum solution is comparable to the 'needle in a haystack' problem. A manual trial and error search for the best retrofit solution using individual simulations would be time consuming, and also restrictive, thus compromising the ability to reach the optimum solution. Therefore, optimisation tools have been used in this study to address the complexity of decision- making.

Context and aims

The paper explores retrofit strategies using a simple box. The invistigation explores various fabric strategies, in order to establish pathways for retrofit of zero carbon houses that are adaptable to the changing climate without compromising the overall performance in the future. The main aim is to investigate conflicting constraints of environmental, social and economic criteria, in the current and future weather.

UK climate projections

The UK Climate Projections 2009 (UKCP09) provide climate information for the UK up to the end of the century. Although weather projections are uncertain, they are crucial to develop future adaptation strategies. The UKCP09 weather projections are based on advanced climate modelling, past observations, the Intergovernmental Panel on Climate Change (IPCC) emissions scenarios and expert judgement. It has three carbon emissions scenarios; high, medium and low to represent the possible future states (UKCIP, 2010).

To quantify the uncertainties in the projections caused by: natural climate variability; modelling uncertainty; and uncertainty in future emissions; probabilistic projections are provided, based on 5 Cumulative Distribution Function (CDF) probability levels (of 10%, 33%, 50%, 66% and 90%) (UKCP09, 2010).

Simulations performed using future weather data allow risk-based analysis and adaptation strategies to be implemented in early design stages.

OPTIMISATION

Optimisation itself refers to finding the best possible solution to a problem, within a set of constraints. The optimisation of building performance would have the optimum design or control as the sought after solution, given a set of variables or alternatives, according to a set criteria. These criteria are represented as a mathematical function, referred to as the objective function. The optimisation results in an optimum solution, on the basis of the objective function, and it could be either a minimum or a maximum of that function (Coello, 2006, Evins, 2013)

Single objective

When dealing with a single objective, such as energy consumption, the solution is a single optimum value, in which case the best possible solution is the minimum energy consumption. This is referred to as the ‘global optimum’. In some cases this might not be reached due to relying on unsuitable methods such as single simulations or search methods that get locked in a local rather than the global optimum. A single objective function is a function of one independent variable y = f(x), which could have local minima as well as a global minimum (Coello, 2006).

Multi-objective optimisation problem

A multi-objective optimisation problem is a problem that has two or more objectives. A multi-objective function is a function of several independent variables $y = f(x_1,x_2,\ldots x_n)$, If the objectives are independent, a global optimum can be reached in sequential order, one single objective at a time. However, this point-to-point search can be very time consuming. Another method would be a weighted sum approach, where various independent objectives are combined to create a single objective. A third approach, used by DesignBuilder through JEPlus, is to conduct parallel search using genetic algorithms. This is by far the fastest way of searching the solution space, and the least likely to lock in an local minimum that effectively represents a sub-optimal solution.

However, in most cases the objectives are not independent between each other. For instance, the objectives could be to minimise energy consumption and maximise thermal comfort. In such cases, there would be no optimum solution due to conflicts between the objectives. The global optimum would not be normally found in a single solution, and trade-offs between conflicting constraints would be required (Coello, 2006, Attia et al., 2013, Lapinskiene and Martinaitis, 2013).

Pareto Optimum

In the case of multi-objective optimisation, where there are conflicting constraints between the objectives, the notion of optimality is different. This is represented by an Edgeworth-Pareto relationship, known as the Pareto optimum. It was firstly introduced by Francis Ysidro Edgeworth in 1881, and generelised by Vilfredo Paerto in 1896 (Coello, 2006).

Using this approach, all objectives are given the same weight, trying to reach a compromise between them, and resulting in a set of trade-off solutions that would create a curve when plotted, known as the Pareto front, where the objectives perform better than on any other point above that curve.

Building design is an inherently multi-objective process, with a trade-off to be made between two or more conflicting design objectives, for example; achieving high thermal comfort would require more energy demand and therefore an increase in carbon emissions. This has led to the application of simulation-based multi-objective optimisation methods that identify the Pareto optimum and the trade-off between the conflicting objectives (Chantrelle et al., 2011).

METHODOLOGY

Previous work by authors proved that climate change would have an effect on the energy consumption of a building due to the increase in cooling demand. This paper is a continuation of an investigation looking at pathways to maintain a zero carbon performance in future weather. These pathways would need to help mitigate climate change as well as provide adaptation strategies in future weather extremes (Jankovic and Huws, 2012).

Deriving the pathways for retrofit requires a series of design decisions, involving various design variables. Therefore, the optimisation was a necessary step to investigate a range of best solutions, without compromising the results.

DesignBuilder software (DesignBuilder, 2014) was selected for the work, due to its readily available optimisation capability, with JEplus as a facilitator of the optimisation process (DesignBuilder, 2014, jEPlus, 2014)

Using DesignBuilder software, a box model was created, and a multi-objective simulation was carried out using the optimisation application within the software. The box model is a simple detached box, with an area of $60m^2$, a flat roof and glazing on the southern elevation. A box was used for simplifying the modelling process, reducing the number of variables and reducing the simulation time required.

The optimisation analysis looked at three groups of design variables; 1) building fabric; 2) cooling strategies, including shading, natural ventilation and mechanical cooling; 3) zero carbon technologies. This paper will introduce the first step of the analysis, investigating optimisation for certain elements of the building fabric.

As the aim of the multi-objective optimisation in this research is to find the best solutions for retrofit, there are three conflicting objectives: reducing carbon emission, reducing cost and providing thermal comfort. Carbon emissions in DesignBuilder represent the total operative carbon over the whole year, including cooling, which was applied to measure the effect of the various variables on reducing the space overheating, and comfort is represented by the yearly number of hours when discomfort is occurring.

Cost within the optimisation function in the software is based only on the construction cost. This was calculated on the basis of the market prices in the 2nd quarter of 2014, which were manually entered into the software by the authors. These prices included the supply of materials and labour cost for installation, as well as main contractor's preliminaries of 12%, overheads and profit of 5%, and a contingency of 5%, but excluding design fees and VAT.

The three objectives of carbon, comfort and cost had equal weighting, as there is no criteria to decide which objective in this case would be of higher priority. After running the optimisation, from the Pareto front of each two objectives, a trade-off could be decided based on the selected objective importance, which would result in compromising the second objective.

The design variables related to the building fabric consisted of: external wall construction, external glazing, window to wall ratio, infiltration, shading and ground thermal mass. The variables were selected to correspond to the most common steps in the retrofit process, such as improvements of thermal insulation and glazing, as well as providing passive ways for reducing future overheating, including thermal mass, window size and shading.

For each one of the variables different options were specified. External wall construction had 6 different options of insulation. Three of them were internal and the other three external insulation, with U-values of 0.1, 0.2 and 0.3 W/m²K, achieved by using Warmcell insulation of varying thicknesses, as shown in (Table 1). The U-value of 0.3 W/m²K is a representative of the building regulations requirement for retrofit.

Glazing consisted of three options: double glazing (1.9 W/m²K U-value), triple glazing (0.86 W/m²K U-value) and quadruple glazing (0.6 W/m²K U-value).

Table 1
External walls and glazing options

VARIABLE	OPTIONS	U-VALUE (W/m²K)
External wall	Internal Insulation 350mm Warmcell	0.10
	Internal Insulation 200mm Warmcell	0.20
	Internal insulation 100mm Warmcell	0.29
	External Insulation 350mm Warmcell	0.10
	External Insulation 200mm Warmcell	0.20
	External insulation 100mm Warmcell	0.29
Glazing	Double glazing	1.90
	Triple glazing	0.86
	Quadruple glazing	0.6

Infiltration was set as a range between 0.1 and 1.0 air changes per hour (ach) in steps of 0.2. Shading consisted of 7 options: 3 different louvers and 4 different overhangs. The ground floor had two options; High thermal mass with rammed earth, Low thermal mass with wood and carpet. Finally the window to wall ratio was set as a range between 20% and 100%.

Carbon emissions in this study are based on the energy demand without taking into account the energy produced from any zero carbon technologies. Those considerations are covered in a later stage of the analysis.

Searching for a needle in a haystack

Table 2 below indicates the solution space size. As it can be seen from this table, with a handful of parameters and relatively small number of variations of each, the total number of possible designs for a single building increases very quickly to over 400,000. No designer can search this solution space exhaustively, and point-to-point search would last a very long time and would easily lock into a local sub-optimum. The problem of searching this space is therefore equivalent of searching for a needle in a haystack, and only a parallel search using a genetic algorithm, such as NSGA2 used by jEPlus (Asadi et al., 2012, jEPlus, 2014) , could find a set of trade-off solutions within reasonable time.

Table 2 The solution space

Parameter	Variations
Wall construction	6
Glazing	3
Floor construction	2
Window to wall ratio: 20% - 100%, steps of 10%	9
Infiltration (ACH): 0.1 – 1.0, steps of 0.1	10
External shading: brie soleil x 4 + louvres x 3	7
Heating set points: 2	2
Building heating systems: gas, biomass, heat pump	3
Renewable technologies: solar PV, solar thermal, wind energy	3
The solution space: the product of the above	408,240

Future weather analysis

It was found that the solutions derived for the Birmingham current weather, resulting in zero carbon emissions and low discomfort, would not be the same in the future weather. Therefore, this study conducted optimisation with the same objectives and variables, using Birmingham future weather files for 2030, 2050 and 2080. These files were of the medium emissions scenario and using the 50th percentile of weather data predictions.

For each weather scenario, on the Pareto front, there will be an optimum point for carbon emissions, which would also have the highest level of discomfort. Moreover, there would be an optimum point for comfort, which would have least hours of discomfort but at the same time highest carbon emissions. Those two optimum points for current, 2030, 2050 and 2080 weather were subsequently simulated individually, by applying the same design variables that led to them, and studying the energy breakdown in the individual models.

Triangulation

The DesignBuilder software has three pre-set objectives; CO2 emissions, discomfort hours and construction costs. However, the user can define only two objectives at a time for each optimisation run.

Having three conflicting objectives in the study required running three optimisations for each weather file; discomfort AND CO2, discomfort AND cost, CO2 AND cost.

EXPERIMENTS AND RESULTS

The multi-objective optimisation for the four different files and the three optimisations for each resulted in 12 Pareto fronts, with 40 points representing different scenarios (Figure 1, Figure 2 & Figure 3). None of the points within a weather Pareto front were identical, which indicated that no single solution would fit the current and the predicted future weather, in terms of both of the specified objectives: carbon and comfort. This therefore indicates the importance of gradual adaptive measures. However, the optimum points for cost were very similar in the outputs, due to the construction cost criteria, which calculated the lower cost solution, in relation to the second objective.

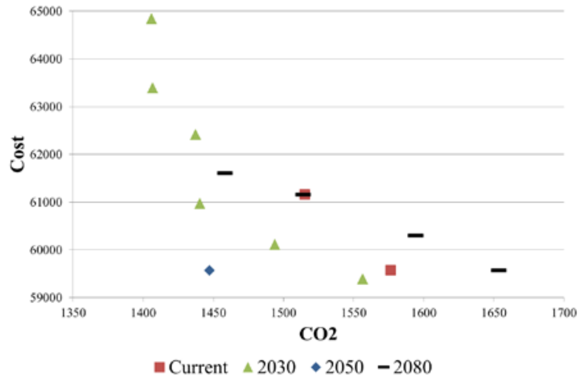

Figure 1 CO2 emissions and cost Pareto fronts

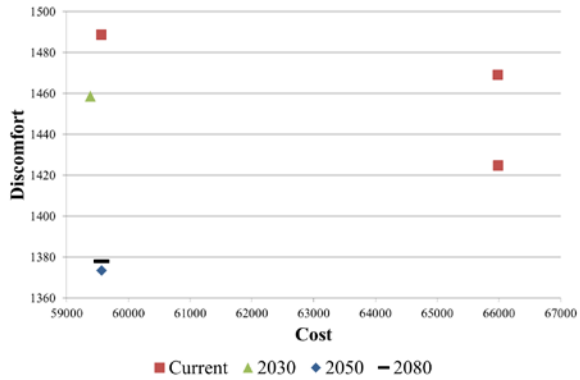

Figure 2 Cost and discomfort hours Pareto fronts

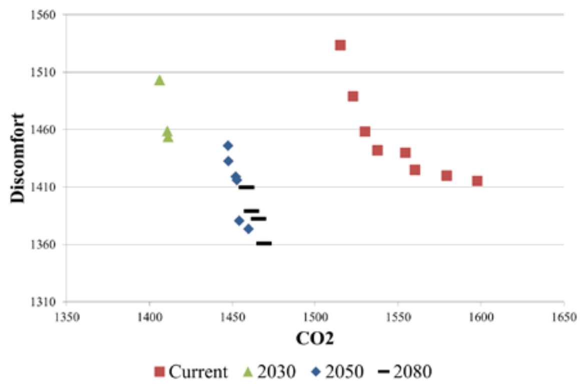

Figure 3 CO2 emissions and discomfort hours Pareto fronts

External Walls

There were six different options for external walls. The results demonstrated the importance of the insulation in reducing both carbon and discomfort.

The two options of internal insulation and external insulation with 350mm of Warmcell, were the two options occurring for the optimum points of minimum CO2 and maximum comfort, with the Internal insulation of 350mm being the dominant option for current and 2080 weather scenarios.

It is noticeable that having the cost as an objective influenced the optimum Pareto points for cost to occur for insulation of 100mm Warmcell, just achieving the Building Regulations requirement.

Glazing

The three options for external glazing were double glazing, triple glazing and quadruple glazing. The results showed that having comfort and CO2 emissions as constrains resulted in mainly triple and quadruple glazing solutions. The results suggest that there is correspondence between triple glazed windows and the optimum comfort points, and correspondence between quadruple glazing and the carbon reduction optimum points. However, it is worth mentioning that a whole building solution is necessary as window size and shading options are closely related to this option.

Having a cost as an objective gave similar results as in the external wall construction, where the lower cost option of double glazing dominated the results (Figure 4).

Window to wall ratio and shading

Earlier test results indicated the need for shading in future weather, when window to wall ratio was not variable. In this box model, both window to wall ratio and shading elements were test variables, and results of both were examined in relation to each other.

In relation to CO2 and comfort only, in the current weather, a combination of 48% glazing on the southern façade and 0.5m overhang resulted in an optimum CO2 emission performance, while more shading was required with a similar glazing area in order to improve comfort.

Results for future weather were suggesting higher window to wall ratio, with the highest amount of glazing in 2050, reaching 80% in combination with 1.5m overhang shading. But the area of glazing reduces again in 2080 to 55% glazing and 1.5 m overhang for both comfort and CO2 optimum point.

When having the cost as an objective, combined with comfort, the results were very similar to the above with slight variations, in terms of less shading. However, when Cost and CO2 are the two objectives, the glazing area increases drastically, to 70% glazing in current weather with 0.5m overhang, and up to 98.5% glazing in 2080 with 0.5m overhang.

Thermal mass

High thermal mass and low thermal mass were tested in the ground floor by changing the surface material. When having comfort and CO2 emissions as objectives, high thermal mass was a dominant solution in all Pareto points for future weather scenarios, with one exception: in order to achieve optimum comfort levels in the current climate, the ground floor had low thermal mass.

Due to the low prices of rammed earth in comparison with having wooden floors, when having cost as an objective, high thermal mass ground floor was the optimum solution in all the points.

Energy and carbon breakdown

Previous studies and analysis showed an increase in total energy demand with the increase of the weather file year. With both Comfort and CO2 emissions set as objectives, the box model had different results in relation to current weather files, as the energy demand was the highest in the current weather, followed by 2080, with minimum energy demands in 2030. However, the increase of energy demand from 2030 to 2050 up-to 2080 was clear. This was disregarding the change of future carbon intensity of fuels and using the current carbon conversion factors.

With cost and CO2 emissions set as objectives, optimisation gave higher carbon emissions for 2080, followed by the current weather file, with 2030 achieving the minimum carbon emissions.

In order to gain better understanding of the carbon emissions related to the Pareto optima, the highest and lowest points in the Pareto front for each optimum point in the current and in 2080 weather file were simulated. The simulation was run using DesignBuilder by applying the design variables of the corresponding points in the model.

The number of the points was related to the triangulation method, where each optimisation of two objectives would have optima for each of the objectives. Hence, the current weather had 6 optimum points.

In some cases where cost and comfort where the two objectives, a single Pareto value was calculated instead of a Pareto front, such as in the case of 2080 weather file, therefore resulting in 5 optimum points for 2080 as shown in Figure 2.

The optimum points related to the current weather file indicated minor cooling demand ranging between 0.002% and 0.5% of the total energy demand, while heating demand ranged between 39%-45% of the total energy demand.

Results from the 2080 weather file optimum points, showed that heating demand still represented the majority of energy demand, but less than the current heating demand, with a range between 30%-33% of the total energy demand, while cooling had a slight rise, varying between 0.7% and 5% of the total energy demand (Figure 4).

These results might not put into perspective the increase in cooling demand that is expected in the future. We need to stress that these are the results of the optimum points, which represent the best solution

Figure 4 Table showing the optimum scenarios for the various objectives, along with the cooling and heating percentage of the total energy demand

Weather file		Current			2080		
Objectives		**Solution**	**Heating %**	**Cooling%**	**Solution**	**Heating %**	**Cooling%**
Discomfort & CO2	Minumum discomfort	Int insulation 350mm, low thermal mass, quadro glazing, 45% southern glazing and 2m overhang	45%	0.00%	Int insulation 350mm, high thermal mass, triple glazing, 55% southern glazing and 1.5m overhang	33%	0.70%
	Minimum CO2	thermal mass, triple glazing, 48% southern glazing and 0.5m overhang	40%	0.10%	Int insulation 350mm, high thermal mass, quadro glazing, 55% southern glazing and 2m overhang	30%	1%
Discomfort & cost	Minumum discomfort	Int insulation 350mm, High thermal mass, quadro glazing, 33% southern glazing and 0.5 overhang	37%	0.02%	Int Insulation 100mm, High thermal mass, double glazing, 66% southern glazing and 0.5 overhang	33%	3%
	Minimum cost	Int insulation 100mm, High thermal mass, double glazing, 95% southern glazing and 0.5 overhang	41.40%	0.49%			
CO2 & cost	Minimum CO2	Int insulation 350mm, High thermal mass, double glazing, 70% southern glazing and 0.5 overhang	38%	0.50%	Ext Insulation 200mm, High thermal mass, double glazing, 98.5% southern glazing and 0.5 overhang	26%	5%
	Minimum cost	Int insulation 100mm, High thermal mass, double glazing, 70% southern glazing and 0.5 overhang	42%	0.50%	Int Insulation 100mm, High thermal mass, double glazing, 98.5% southern glazing and 0.5 overhang	31%	5.30%

related to the

objectives. It could be said that cooling was reduced due to the passive strategies applied in the model, and the fact that the internal gains were limited due to the model simplicity, which reduced the heat load. This could also explain the high heating energy demand, inrelation to the large external surface area.

DISCUSSION

The results indicate that no single solution would fit the current and the predicted future weather in this particular retrofit case, in terms of the three set objectives: carbon, comfort and cost. This indicates the necessity of adaptive measures to be integrated into buildings along with the mitigation measures. It also highlights the importance of gradual adaptive measures that could be derived from the Pareto results for the future weather.

However, patterns were identified between the variables and the objectives. The results demonstrated the importance of high levels of thermal insulation in external walls. In this case of a detached box, internal insulation was dominant in the current and in the 2080 weather, corresponding to both thermal comfort and CO2 optimum. This was in combination with high thermal mass in all future scenarios, which would help stabilise the internal temperatures and improve comfort. However, the optimum points in the current weather had internal insulation of 350mm, combined with low thermal mass flooring.

A clear pattern was occurring with the type of glazing, where triple glazing corresponded to lower carbon emissions, while quadruple glazing corresponded to increased comfort. The initial assumption of the reason why quadruple glazing was corresponding to higher CO2 emissions was an increase in cooling demand. However, the results did not support this assumption, as glazing is just one variable within the combination of variables, which restricts the ability to detect the relationship between a single variable and a result.

With comfort and CO2 emissions as objectives, the window to wall ratio was the lowest in current weather, due to the need to reduce the amount of heat loss occurring through the windows. While the area of glazing increased in 2030 and 2050 weather up to 80%, it reduced back again in 2080 to 55%, in order to minimise solar gains through the glazing. In the current weather, shading was mainly required to achieve the lowest discomfort level. However, in 2080, the 1.5m Overhang was required to reduce both discomfort and CO2 emissions.

Having cost as an objective resulted in limited number of solutions of 6 Pareto points, due to the limited measures to reduce the cost in this simple box. To achieve the low cost target, 100mm of internal insulation was combined with rammed earth and double glazing, window to wall ratio of a maximum of 98.5%, and a minimum shading of 0.5m overhang.

Results from the energy breakdown identified heating as the main source of carbon emissions in both current and future climate. However, heating demand reduced by 25% from current to 2080 weather, whilst, cooling demand was insignificant in current weather, but reached 5% of the total demand in 2080. This magnitude is not significant, but it was a result of the optimum combination to reduce the carbon emissions, using passive strategies. Therefore, if no adaptation measures are deployed, the demand will be higher.

CONCLUSION

Deriving the pathways for retrofit requires a series of design decisions, involving various design variables. Optimisation was found to be a necessary step to investigate a range of best solutions, without compromising the results.

A model of 60m^2 detached box was used to investigate various fabric strategies, in order to establish pathways for retrofit of zero carbon houses that are adaptable to the changing climate without compromising the overall performance in the future.

The multi-objective optimisation had three conflicting objectives: reducing carbon emissions, reducing construction cost and providing thermal comfort. The design variables related to the building fabric consisted of external wall construction, external glazing, window to wall ratio, infiltration, shading and thermal mass. Optimisation analysis was run using Birmingham current weather files, and future weather files for 2030, 2050 and 2080.

The results showed that none of the points within the 12 Pareto fronts were identical, which indicated that no single solution would fit the current and the predicted future weather at the same time, in terms of the specified objectives: carbon, cost and comfort.

High levels of interal insulation was defined as an optimum solution for various weather files, to reduce both CO2 emissions and discomfort levels. That was combined with high thermal mass, particularly in future climates. However, Pareto points related to comfort optima were dominated by qudruple glazing, while the points related to CO2 emissions optima were dominated by triple glazing, whilst double glazing corresponded to the cost optima points, indicating a need for a trade-off between carbon emissions and comfort criteria.

Due to the simplicity of the model, measures to reduce the cooling demand were highly effective, in comparison to more complex buildings. This emphasized that strategies that target the fabric, and rely on passive measures to improve building's performance are essential, but currently expensive.

The Pareto front included different solutions which enabled a compromise between the three objectives. If we anticipate that the carbon intensity of future electricity would decrease, and that carbon emissions would be reduced with the integration of renewables, together with a possible price reduction for advanced materials, then this would give scope for more emphasis on comfort in the future.

NOMENCLATURE

ACH,	Air Changes per Hour;
CCD,	Cooling Degree Days;
CFD,	Cumulative Distribution Function;
$IPCC$,	Intergovernmental Panel on Climate Change;
NSGA2,	Non-dominated Sorting Genetic Algorithm 2
$UKCP$09,	UK Climate Projections 2009;
ZCH,	Zero Carbon House.

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